Density Control and Limit(s) in MST

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Abstract

The MST RFP is fueled by gas puffing and pellet injection. Line-averaged densities (n_e) approaching and exceeding the Greenwald limit (n_G) have been achieved. In some discharges, the plasma terminates early when n_e exceeds n_G. In others, n_e exceeds n_G without premature termination. While not yet approaching n_G, we have increased n_e by 70% in improved confinement PPCD plasmas with pellet injection. Modification of sawtooth behavior is observed in high density standard plasmas fueled by pellets and/or gas puffing. Measurements with a multichord far infrared interferometer/polarimeter show that pellet injection peaks the density profile, raising the central density to >4×10^{13} cm^{-3}, while flattening the current profile. Presently, the density achievable with gas puffing is limited by the throughput (~75 Torr*L/s per valve for D_2) of MST’s puff valve system. A single valve has been modified for higher throughput (~600 Torr*L/s) to achieve higher densities.
Outline

• Introduction
• The Greenwald Limit
• Fueling Methods
• Experimental Setup
• Effects on Electron and Current Density Profiles
• Effects on PPCD plasmas
• Summary
• Future Work
Motivation

• Density profile control
  – Affect sawtooth crash behavior in standard discharges via current profile control
  – Raise $<n_e>$ in PPCD discharges without triggering fluctuations
  – Control of electron density and/or current density profile can affect RFP confinement

• Establish $n_e$ limit
  – Density limits in the reversed field pinch haven’t been as widely studied as in the tokamak
  – Does the Greenwald limit represent a boundary in RFP operational space?
  – If there’s a density limit, perhaps methods can be found to surpass it, e.g., like pellet injection in tokamaks
  – Perhaps the physics of the limit can be ascertained
The Greenwald Limit

• Empirical limit characterizing central line-averaged density in tokamaks\(^1\) defined as:
  \[ n_G = \frac{I_P}{\pi a^2} \]

• When \(n_e\), central line averaged density, exceeds \(n_G\), the discharge can be quenched, sometimes disruptively, with \(I_P\) going to zero rapidly

• Physics of this limit is not yet established

• Has been overcome in some cases with pellet injection

Previous RFP Results

- RFX has seen $<n_e>$ limited to $n_G$ during current ramp down\(^1\)
- Other RFPs have seen $<n_e>$ exceeding $n_G$ during startup either before (and sometimes just as) the toroidal field at the wall reverses\(^2,3\)
- Exceeded $n_G$ transiently with pellet injection as well as during the current ramp down phase on MST\(^4\)

Fueling Methods
Edge Gas Puffing

• MST fueling system
  – 6 Veeco PV-10s spaced toroidally around MST
  – System flow rate for 150 V pulse and 50 psi of D$_2$: 450 Torr•L/s
  – Multiple puffs/shot of variable (<5 ms) duration with negligible time between consecutive pulses

• Modified puff valve
  – PV-10 with throat bored out to larger diameter (1.07 mm)
  – Flow rate with 350 V pulse and 50 psi of D$_2$: 660 Torr•L/s
  – Single puff/shot of variable (<10 ms) duration
Modified puff valve exhibits more attractive flow characteristics

- Valves were tested with both deuterium and hydrogen at 50 PSI
- Original MST valves 9372C and 9369C are of indeterminate history but are believed to not have been modified
Pellet Injection

- MST has a 4-barrel pellet injector built by ORNL
- D$_2$ pellets of 1.0 mm to 1.6 mm diameter
- Pellets propelled by high pressure (1000 PSI) H$_2$ and/or mechanical punch to speeds in the range of 100 m/s to 1200 m/s
- Capable of firing 4 pellets/plasma discharge
- Pellets are injected radially 30° above horizontal midplane from outboard side
Experimental Layout

- CO$_2$ Interferometer (central line-averaged density measurement)
- Modified Puff Valve
- MST puff valves (6)
- 11-chord FIR interferometer and polarimeter (electron and toroidal current density profile measurement)
- Pellet Injector
Profile Effects
Particle inventory increase similar for pellets and intense gas puffing

- During both pellet injection (blue shaded region) and intense gas puffing (green shaded region) the Greenwald density for MST is exceeded (red trace)
- Change in particle inventory for each case is roughly the same

![Particle Inventory Diagram](image1)

![Comparison to Greenwald Density Diagram](image2)
If $n_e$ exceeds $n_G$ for sufficiently long times the discharge terminates

- 1.6 mm pellets fired into both discharges with the following arrival times and speeds: Shot A - 14 ms, 133 m/s and Shot B - 17 ms, 144 m/s
- Shot A is termed a stable discharge and B, a destabilized discharge where the $<n_e>$ exceeds $n_G$ for a longer period than in A
- Both shots produce decay in the plasma current, with A recovering
Pellet injection and intense edge puffing affect the electron density profile differently

- The intense gas puff lasts for 10 ms (shaded region)
- The shaded region represents the approximate path based on maximal penetration of two slow pellets
- Both shots are low current, $I_p \sim 200$ kA
- The intense gas puff results in an extremely hollow profile, with $n_e(\text{edge}) \sim 2n_e(\text{core})$
- Pellet injection (following full ablation of the pellets) results in a centrally peaked profile
Closer look at the profile effects

- For intense gas puff shot:
  - 10 ms: start of puff
  - 15 ms: middle of puff
  - 20 ms: end of puff
  - 25 ms, 30 ms: after puff

- Pellet shot:
  - 16 ms: before injection of pellets
  - 19 ms: pellets have penetrated the core
  - 21 ms: pellets probably fully ablated
  - 24 ms, 30 ms: after full ablation
Pellets and intense edge puffing alter the nature of sawteeth

- Shot A had an intense gas puff from 10 to 20 ms. Peak density is reached at ~21 ms.
- Shot B had 2 slow pellets fired into the plasma at 17-18 ms. The peak $\langle n_e \rangle$ was reached at ~21 ms.
- For the pellet-injected shot, the bursts in edge ($m=0$, $n=1-4$) activity decrease in amplitude.
- For the high density edge fueled shot (A), the baseline of edge fluctuations increases, though the amplitude of the bursts decreases.
- In both cases, the baseline of core ($m=1$, $n=6-10$) fluctuations increases.
Pellets peak, then flatten the toroidal current density profile

- Shaded region approximates pellet trajectories for a 1.3 mm and 1.6 mm pellet (v > 200 m/s for both) based on maximal penetration
- While the pellets are in the edge, (~19 ms) the current profile peaks, at which point $n_e(r)$ is hollow
- As the pellets make it closer to the core, $n_e$ peaks, and $J_{tor}$ flattens (~21 ms)
Intense edge puffing results in very hollow profiles at high and low $I_p$

$I_p = 200 \text{ kA}$

$I_p = 400 \text{ kA}$

Gas puff duration
Pellet injection into PPCD
Improved Confinement Plasmas

- Improved confinement achieved through PPCD (pulsed poloidal current drive) programming of discharge
- PPCD is used to control m=0 and m=1 fluctuations

**q-Profile**

- Improved confinement w/o pellet
  - Line Averaged Density ($10^{13}$ cm$^{-3}$)
  - Core mode ($m=1$, $n=6-10$) amplitude
  - Edge mode ($m=0$, $n=1-4$) amplitude

- The goal of pellet injection into PPCD plasmas is to increase $\langle n_e \rangle$ and still suppress m=0 bursts (there’s an empirical limit for $\langle n_e \rangle$ above which m=0 bursts are difficult to control)
Comparison of electron density with (3) fueling techniques in PPCD Plasmas

- Toroidal plasma current of 200 kA
- Three types of shots:
  (A) No external fueling (other than recycling) during PPCD – standard mode of operation
  (B) Gas puffing during PPCD (w/o new puff valve)
  (C) (2) pellets injected near start of PPCD (no gas puffing)
Edge-resonant Magnetic Fluctuation Comparison

- Edge fluctuations remain low during the burst free period (shaded areas) w/o gas puffing, (A), and with pellet injection (C).
- With gas puffing, (B), no m=0 bursts but fluctuations are larger.
Core-resonant Magnetic Fluctuation Comparison

- Core fluctuations remain low w/o gas puffing, (A), and with pellet injection, (C)
- Again, with gas puffing during PPCD, (B), fluctuations are larger
- Encouraging that edge and core fluctuations remain low with pellet injection
- Higher density with reduced fluctuations could mean higher $\beta$
Summary

• Intense gas puffing and/or pellet injection can lead to densities greater than the Greenwald density
• However, the effect is transient and sustainment of this high density has yet to be attempted
• Pellets peak the current density profile while passing through the plasma edge
• Once they penetrate the core, the current profile is flattened
• Pellet injection and intense gas puffing increase the plasma particle inventory but with maximal deposition in different regions of the plasma
• Pellet injection immediately preceding PPCD can lead to higher density plasmas with low magnetic fluctuations
• More recent experiments show that it is possible to reach \( <n_e> \approx 1.7 \times 10^{13} \text{ cm}^{-3} \) while keeping fluctuations low during pellet injection into PPCD
Future Work

• Sustainment of densities greater than $n_G$ in both pellet injected and intensely gas puffed plasmas at various plasma currents - Do plasmas reliably terminate?

• Profile ($T_e$, $n_e$, $J_{TOR}$) measurements for pellet fueled discharges, both PPCD and standard - in the process measuring $\beta$

• Attempt pellets into QSH plasmas